Nuclear reactions in the Sun after SNO and KamLAND

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Summary. In this brief review we discuss the possibility of studying the solar interior by means of neutrinos, in the light of the enormous progress of neutrino physics in the last few years. The temperature near the solar center can be extracted from Boron neutrino experiments as: $T = (1.57 \pm 0.01)\, 10^7\, K$. The energy production rate in the Sun from pp chain and CNO cycle, as deduced from neutrino measurements, agrees with the observed solar luminosity to about twenty per cent. Progress in extracting astrophysical information from solar neutrinos requires improvement in the measurements of $^3He + {}^4He \rightarrow {}^7Be + \gamma$ and $p + {}^{14}N \rightarrow {}^{15}O + \gamma$.

1 Introduction

Some fourty years ago John Bahcall and Raymond Davis started an exploration of the Sun by means of neutrinos [1, 2]. Their journey had a long detour, originating the so called solar neutrino puzzle: all experiments - performed at Homestake, Kamioka, Gran Sasso and Baksan and exploring different portions of the solar neutrino spectrum - reported a deficit with respect to the theoretical predictions. Were all the experiments wrong? Or were the Standard Solar Model (SSM) calculations inadequate? Or something happened to neutrinos during their hundred million km trip from Sun to Earth?

After thirty years the SNO experiment, with its unique capability of collecting and distinguishing events from ν_e and from neutrinos of different flavour, has definitely proved that the missing electon neutrinos from the Sun have changed their flavour [3]. This effect has been confirmed by KamLAND: man made electron antineutrinos from nuclear reactors disappear during their few hundreds km trip to the detector [4].

The enormous progress of the last few years is summarized in Fig. 1. A global analysis of solar and reactor experiments yields for the oscillation parameters $\delta m^2 = 7.1^{+1.2}_{-0.6}\, 10^{-5}\, eV^2$ and $\theta = 32.5^{+2.4}_{-2.3}$ degrees [5], see also [6, 7, 8].

Really we have learnt a lot on neutrinos: their survival/transmutation probabilities in vacuum and in matter are now substantially understood. There is still a long road for a full description of the neutrino mass matrix, however now that we know the fate of neutrinos we can exploit them.

In this spirit we can go back to the original program started by Davis and Bahcall and ask what can be learnt on the Sun from the study of neutrinos. This question is clearly connected with the knowledge of nuclear reactions in the Sun and in the laboratory. Each component of the solar neutrino flux (pp, Be, B ...) is determined by physical and chemical properties of the Sun (density,

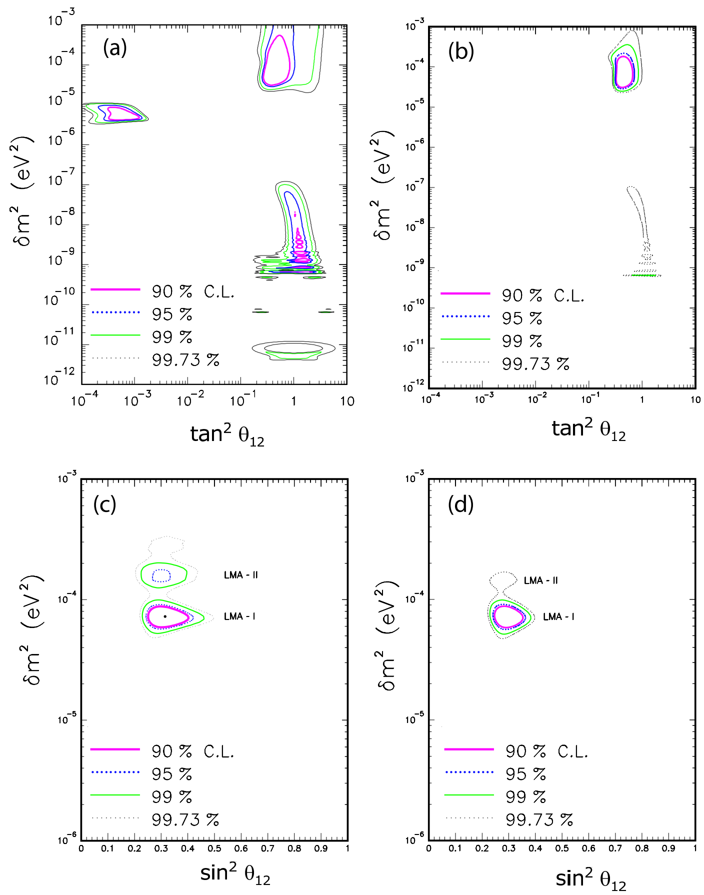


Fig. 1. Global analysis of solar and terrestrial neutrino experiments. (a) Before SNO results, (b) including SNO-phase I, (c) including KamLAND results, (d) including SNO-salt phase. From [8, 9, 10]

temperature, composition...) as well as by the cross sections of the pertinent nuclear reactions. The knowledge of these latter is thus crucial for extracting information on the solar interior from neutrino observations.

In this short review we shall discuss a few items:
i) what can be learnt on the Sun from measurement of the Boron flux?
ii) what can be learnt about energy generation in the Sun from solar neutrinos?
iii) which nuclear physics measurements are now crucial for extracting astrophysical information from solar neutrino experiments?

2 The Boron flux: nuclear physics and astrophysics

Among the various branches of the pp-chain, see Fig. 2, the status of ^8B neutrinos, the component originating from the pp-III branch, is unique in two respects:

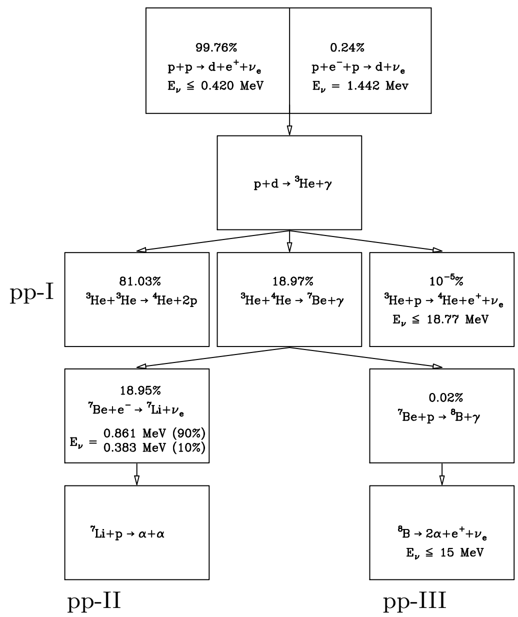


Fig. 2. The pp-chain. Probabilities of the different branches and the neutrino energies are indicated.

i) experiments as SNO and SuperKAMIOKANDE are sensitive to these neutrinos only (whereas the signal in Chlorine and Gallium radiochemical experiments is a weighted sum of several components);
ii) the total active neutrino flux from ^8B decay $\Phi_B = \Phi(\nu_e + \nu_\mu + \nu_\tau)$ is now a measured quantity.

By combining the final SuperKAMIOKANDE electron scattering data and the latest SNO charged and neutral current fluxes one obtains [8]:

$$\Phi_B = 5.5\,(1 \pm 7\%)10^6 cm^{-2} s^{-1} \quad (1\sigma)\,, \tag{1}$$

in good agreement with the predictions of recent SSM calculations, all prior to this important experimental result, see Table 1.

Table 1. Predictions of some recent SSM calculations compared with experimental result.

	EXP.	THEORY		
	[8]	BP01 [11]	FRANEC [12]	GARSOM [13]
$\Phi_B\,[10^6 cm^{-2} s^{-1}]$	$5.5(1 \pm 7\%)$	5.05	5.20	5.30
$T\,[10^7 K]$		1.5696	1.569	1.57

Table 2. Neutrino fluxes, central solar temperature and solar model inputs. Each column contains the logarithmic partial derivates of the neutrino fluxes and T with respect to the parameter shown at the top of the column. All the values have been computed with FRANEC including elemental diffusion. Generally there is good agreement with [16]: in parenthesis we report the corresponding values from [16] when the difference exceeds 10%.

	Nuclear					Astrophysical				
	S_{11}	S_{33}	S_{34}	S_{17}	$S_{1\,14}$	*lum*	*comp*	*opa*	*age*	*dif*
pp	0.114	0.029	-0.062	0	- 0.019	0.73	-0.076	-0.12	-0.088	-0.02
	(0.14)								*(-0.07)*	
Be	-1.03	-0.45	0.87	0	-0.027	3.5	0.60	1.18	0.78	0.17
					(-0.00)				*(0.69)*	
B	-2.73	-0.43	0.84	1	-0.02	7.2	1.36	2.64	1.41	0.34
					(+0.01)					
N	-2.59	0.019	-0.047	0	0.83	5.3	1.94	1.82	1.15	0.25
									(1.01)	
O	-3.06	0.013	-0.038	0	0.99	6.3	2.12	2.17	1.41	0.34
		(0.02)	*(-0.05)*							
T	-0.14	-0.0024	0.0045	0	0.0033	0.34	0.078	0.14	0.083	0.016

The seven per cent accuracy, which is already remarkable, could be possibly improved in the next few years, as a consequence of higher statistics and better experimental techniques.

The Boron flux, as well as the other components, depends on several nuclear physics and astrophysical inputs X, see e.g. [14, 15]. Scaling laws give the variation of fluxes with respect to SSM calculations when the input parameter X is slightly changed from the SSM value X_{SSM}:

$$\Phi_i = \Phi_i^{SSM} \, (X/X^{SSM})^{\alpha_X} \tag{2}$$

The power law coefficients α_X, derived with FRANEC models including diffusion, are collected in Table 2. Generally there is excellent agreeement between our calculated values and those in ref. [16].

For the Boron flux one has:

$$\begin{aligned} \Phi_B = \Phi_B^{SSM} \, & s_{33}^{-0.43} \, s_{34}^{0.84} \, s_{17}^{-1} \, s_{e7}^{-1} \, s_{11}^{-2.7} \\ & \cdot \; lum^{7.2} \, comp^{1.4} \, opa^{2.6} \, age^{1.4} \, dif^{0.34} \end{aligned} \tag{3}$$

where for each parameter $x = X/X^{SSM}$. The first line contains the nuclear physics parameters (S_{ij} are the astrophysical factors at zero energy for nuclear reactions $i + j$), and the second line groups the astrophysical inputs:
-$lum = (L/L_\odot)$ expresses the sensitivity to the solar luminosity;

-*comp* = $(Z/X)/(Z/X)^{SSM}$ accounts for the metal content of the solar photosphere;
-*age* = $(t/t_\odot)$ expresses the sensitivity to the solar age;
-*opa* and *dif* are uniform scaling parameters with respect to the opacity tables and the diffusion coefficients used in SSM calculations.

Eq. 3 shows that from a flux measurement one can learn astrophysics if nuclear physics is known well enough.

2.1 The uncertainty budget on Φ_B

In Table 3 we present the uncertainty budget, including errors on the inputs and the propagated effect on Φ_B. This table deserves several comments.

i)In the last few years there has been a significant progress in the experimental study of low energy nuclear reactions. In particular LUNA performed in the underground Gran Sasso laboratory has measured the $^3He +^3 He \rightarrow^4 He + 2p$ down to solar energies, avoiding extrapolations. This resulted in a reliable determination of S_{33} with 6% accuracy [17].

ii) Concerning the reaction $^7Be + p \rightarrow^8 B + \gamma$, until a few years ago the uncertainty on the astrophysical factor was at the level of 10-15%: two reviews, published in 1998, recommended $S_{17} = 19^{+4}_{-2}$ eVb [18] and $S_{17} = 21 \pm 2$ eVb [19]. Several new experiments were performed in the last few years, see Table 4.

Table 3. Uncertainties budget on Boron neutrino flux. All the values are at 1σ level.

Source	$\Delta X/X$ (%)	$\Delta\Phi_B/\Phi_B$ (%)
S_{33}	6^*	3
S_{34}	$9^\dagger$	8
S_{17}	5	5
S_{e7}	$2^\dagger$	2
S_{11}	$2^\dagger$	5
lum	$0.4^\ddagger$	3
comp	7	10
opa	2.5^{**}	7
age	$0.4^\ddagger$	0.6
dif	10	3
Exp.		7

* from [17]; † from [18]; ‡ from [20]; ** from [21]

Quite recently new measurements have been presented [22], ranging from E_{cm} = 116 to 2460 keV, and incorporating several improvements over the previously published experiment [23]. This new measurement yields S_{17} = $22.1 \pm 0.6(expt) \pm 0.6(theor)$ eVb based on data from $E_{cm} = 116$ to 362 keV. The central value is obtained from the theoretical shape predicted by Descouvemont and Baye [24]. The theoretical error is based on the fit of 12 different theories to the low energy data.

In addition Junghans et al. [22] compare the results of all "modern" direct experiments, by using the same theoretical curve in fitting the data. They find:

$$S_{17} = 21.4 \pm 0.5\, eVb \quad E_{cm} < 425\, KeV \quad \chi^2/d.o.f. = 1.2 \tag{4}$$

$$S_{17} = 21.1 \pm 0.4\, eVb \quad E_{cm} < 1200\, KeV \quad \chi^2/d.o.f. = 2.1\,. \tag{5}$$

The fit at the low-energy region is quite good, whereas the wide-range suggests that some of the uncertainties may be underestimated. In conclusion, they recommend as "best" value:

$$S_{17} = 21.4 \pm 0.5(expt) + 0.6(theor)\, eVb \quad (1\sigma). \tag{6}$$

We remind however that the low-energy global fit is dominated by the data of ref. [22], all other "modern" experiments yielding somehow lower S_{17} values. Indirect methods for determining S_{17} (Coulomb dissociation, heavy ion transfer and breakup) also suggest a somehow smaller value. In conclusion it looks that a 5% accuracy on S_{17} has been reached.

Table 4. Results on S_{17} from direct capture experiments.

$S_{17}(0)$ $[eVb]$	Ref.
19^{+4}_{-2}	Adelberger et al. compilation [18]
21 ± 2	NACRE compilation [19]
20.3 ± 1.2	Hass et al. [25]
$18.8 \pm 1.7^{\dagger}$	Hammache et al. [26]
18.4 ± 1.6	Strieder et al. [27]
21.2 ± 0.7	Baby et al. [28]
22.1 ± 0.6	Junghans et al. [22]

† theoretically uncertainty included

iii) Concerning the metal fraction Z/X, by using the values reported in [29] and by propagating the individual uncertainties one finds [37]:

$$Z/X_{\odot} = 0.0233 \pm 0.0166 \quad (1\sigma). \tag{7}$$

This 7% uncertainty is similar to that estimated in [20], on the grounds of the spread among the Z/X estimates published from 1984 until 1993.

iv) With regards to the diffusion coefficient, we assume a 10% uncertainty on the grounds that larger variations would spoil the agreement with helioseismic results [30].

Our uncertainty budget is similar to that presented in [31], the main difference regarding the error on S_{17} (Bahcall refers to the Adelberger estimate). Also, concerning the effect of diffusion, a more conservative estimate is adopted in [31], where the uncertainty is obtained by comparing models with and without diffusion.

In conclusion the accuracy on the measured Boron neutrino flux is already comparable to astrophysical uncertainties of the solar model. The 9% error of S_{34} is presently the main source of uncertainty for extracting information on solar properties from the measurement of the ^8B neutrino flux. In this respect, the planned new measurement of $^3He +^4 He$ cross section by LUNA at Gran Sasso is most important.

2.2 The central solar temperature

As well known Boron neutrinos are an excellent solar thermometer, since the produced flux depends on a high ($\simeq 20$) power of the temperature near the solar center T. It is now time to rediscuss this possibility of exploring the solar interior since the produced flux has been measured.

We remind that T is not an independent quantity, its value being the result of the physical and chemical properties of the star. Actually, the various inputs to Φ_B in eq. 3 can be grouped according to their effect on T. All nuclear inputs but S_{11} only determine the weight of the different branches ppI/ppII/ppIII without changing solar structure and temperature. On the other hand, to a large extent the effect of the others can be reabsorbed into a variation of the central solar temperature, almost independently on the way we use to vary it, see Fig. 3.

This is shown more quantitatively in Table 5, where one sees a near constancy of $\alpha/\beta = \frac{\partial ln\Phi}{\partial lnX}\frac{\partial lnX}{\partial lnT}$. the values in the last column. In summary we can write:

$$\Phi_B = \Phi_B^{SSM}(T/T^{SSM})^{20}s_{nuc} \tag{8}$$

where the coefficient 20 is an average of the calculated α/β (see Table 5) and $s_{nuc} = s_{33}^{-0.43}\, s_{34}^{0.84}\;\; s_{17}^{-1}\, s_{e7}^{-1}$

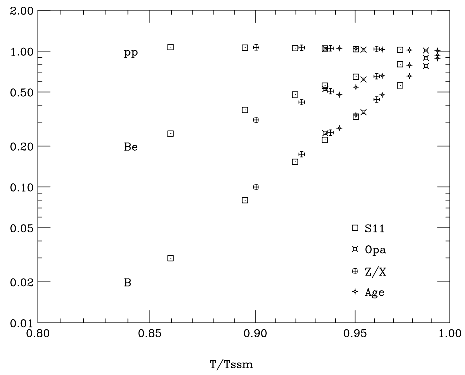
The agreement of theory and experiment on the Boron neutrino flux means thus that we can take $T = 1.57\,10^7\,K$ as the solar temperature in the region where Boron neutrinos are produced [15]. The present experimental uncertainty on Φ_B (7%) and the error on s_{nuc} (10%) yield:

$$\Delta T/T = 0.6\% \tag{9}$$

where the main uncertainty arises from S_{34}. In other words, a crucial prediction of SSM has been verified with neutrinos with an accuracy better than 1%.

A comparison with helioseismology is useful. Helioseismology allows us to look into the deep interior of the Sun, see e.g. [34, 11]. The highly precise measurements of frequencies and the tremendous number of measured lines enable us

a)



b)

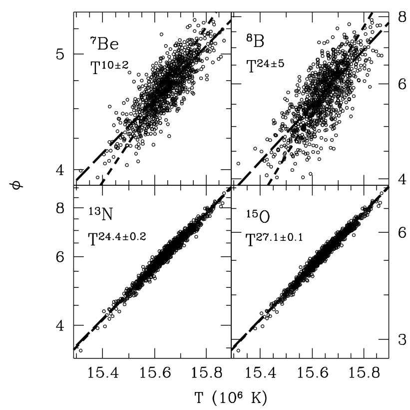


Fig. 3. The behaviour of pp, Beryllium, and Boron neutrinos as a function of the central temperature T when varying different input parameters, a) from [32], b) from [33].

to extract both the properties of the convective envelope (depth, helium abundance) and the sound speed along the solar profile with high accuracy. This latter quantity is determined to the level of about 0.15% in a large portion of the Sun. The accuracy degrades to about 1% near the center, see Figure 4.

From helioseismic observations one cannot determine directly the temperature of the solar interior, as one cannot determine the temperature of a gas from the knowledge of the sound speed unless the chemical composition is known.

However, it is possible to obtain the range of helioseismic allowed values of the central temperature T, by selecting those solar models which are consistent with seismic data. More specifically, in ref. [35] the central temperature T_{helios} has been determined as that of the model which gives the best fit to the seismic data. The uncertainty, ΔT_{helios}, corresponds to the range spanned by models consistent with these data. This results in $T_{helios} = 1.58\,10^7 K$, in good agreement with the SSM predictions, and $\Delta T/T_{helios} = 0.5\%$ at 1σ.

Table 5. Central solar temperature and B neutrino flux.

Source	$\partial lnT/\partial lnX$	$\partial ln\Phi_B/\partial lnX$	
	β	α	α/β
S_{33}	0	-0.43	
S_{34}	0	0.84	
S_{17}	0	1	
S_{e7}	0	-1	
S_{11}	-0.14	-2.7	19
lum	0.34	7.2	21
$comp$	0.08	1.4	17
opa	0.14	2.6	19
age	0.08	1.4	17
dif	0.016	0.34	21

The neutrino result, which is much more direct, is an excellent confirmation of helioseismic inferences. The accuracies of the two methods are already comparable and one can expect neutrinos to become more accurate as better flux and cross sections measurements will be available.

2.3 The sun as laboratory

In the next few years one can envisage a measurement of the solar temperature near the center with an accuracy of order of 0.1 per cent, as the result of progresses in neutrino and nuclear physics. This can be relevant in several respects:
1) it will provide a new challenge to SSM calculations;
2) it will allow a determination of the metal content in the solar interior, which has important consequences on the history of the solar system [37];
3) one can find constraints (or surprises, or even discoveries) on several issues, as e.g. axion emission from the sun, the physics of extra dimensions, dark matter...

All this shows that the Sun is really becoming a laboratory for astrophysics and fundamental physics.

3 pp-chain, CNO cycle or what else?

According to our understanding of the Sun, most of its power originates from the pp-chain, with a minor contribution ($\approx 1\%$) from the CNO cycle. Although this is theoretically well grounded, an experimental verification is clearly welcome.

From the theoretical point of view, solar model predictions for CNO neutrino fluxes are not precise because the CNO fusion reactions are not as well studied

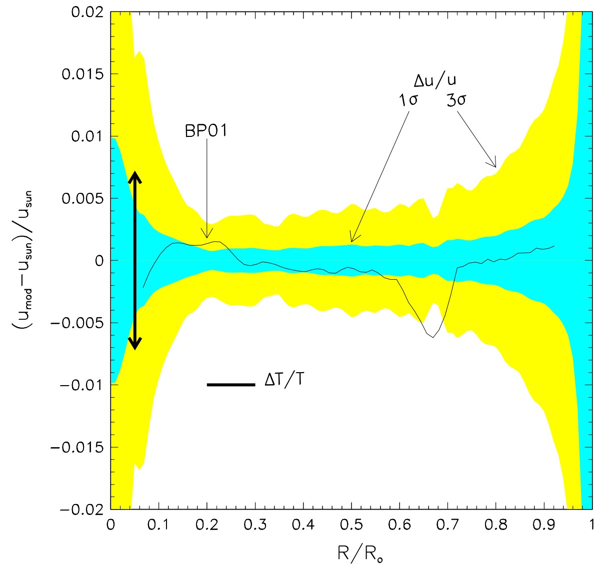


Fig. 4. The dark (light) shaded area corresponds to the 1σ (3σ) uncertainty on helioseismic determination of squared isothermal sound speed $U = P/\rho$ [36]. The relative difference between the SSM prediction [11] and the helioseismic data is also shown (thin line). The present uncertainty on the the solar temperature as derived by the measurement of Boron neutrino flux is indicated with the thick line.

as the pp reactions, see Table 6. Also, the Coulomb barrier is higher for the CNO reactions, implying a greater sensitivity to details of the solar model.

The principal error source is $S_{1\,14}$, the astrophysical S-factor of the slowest reaction in the CNO cycle, $^{14}N(p,\gamma)^{15}O$. At solar energies this reaction is dominated by a sub-threshold resonance at -504 keV, whereas at energies higher than 100 keV it is dominated by the 278 keV resonance, with transitions to the ground-state of ^{15}O or to the excited states at energies of 5.18 MeV, 6.18 MeV and 6.79 MeV.

According to Schroeder et al. [38], who measured down to 200 keV, the main contribution to the total S-factor at zero energy comes from the transitions to the ground state of ^{15}O and to its excited state at $E_x = 6.79$ MeV. In particular, they give $S_{1\,14} = 3.20 \pm 0.54$ keVb. Angulo et al. [39] reanalyzed Schroeder experimental data using an R-matrix model. They obtained $S_{1\,14} = 1.77 \pm 0.20$ keVb, a factor 1.7 below that of [38]. LUNA at Gran Sasso will soon clarify this uncertainty: high accuracy data have been taken down to 180 keV and the preliminary results [40] show the possibility of LUNA to discriminate between the two different extrapolation.

From a global analysis of solar neutrino experiments [41], Bahcall et al. derived an upper limit (3σ) of 7.8% (7.3% including the KamLAND measurements) to the fraction of energy that the Sun produces via the CNO fusion cycle.

Table 6. Uncertainties budget on CNO neutrino flux. All the values are at 1σ level. See Table 3 for estimates of $\Delta X/X$.

Source	$\Delta X/X$ (%)	$\Delta\Phi_N/\Phi_N$ (%)	$\Delta\Phi_O/\Phi_O$ (%)
S_{33}	6	0.1	0.08
S_{34}	9	0.4	0.3
S_{17}	5	0	0
S_{e7}	2	0	0
S_{11}	2	5	6
$S_{1\,14}$	$^{+11}_{-46}$ †	$^{+9}_{-38}$	$^{+11}_{-46}$
lum	0.4	2	3
$comp$	7	13	15
opa	2.5	5	5
age	0.4	0.46	0.56
dif	10	3	3

† from [18]

As mentioned at the beginning of this subsection, the important underlying questions are: is the Sun fully powered by nuclear reactions? Are there additional energy losses, beyond photons and neutrinos?

The idea that the Sun shines because of nuclear fusion reactions can be tested accurately by comparing the observed photon luminosity of the Sun $L_\odot(\gamma)$ with the luminosity inferred from measurements of solar neutrino fluxes, $L_\odot(\nu)$. In fact for each fusion of four proton into a Helium nucleus

$$4p + 2e^- \rightarrow^4 He + 2\nu_e \tag{10}$$

an energy $Q = 26.73$ MeV is released together with two neutrinos. If one determines from experiments the total neutrino production rate one is also determining the energy production rate in the Sun by means of (10), see sect. 2.1 of [14].

Bahcall and Pena-Garay [42] performed a global analysis of all the available solar and reactor data to determine the 1σ (3σ) allowed range for $L_\odot(\nu)$. For the ratio to the accurately measured photon luminosity, they find:

$$\frac{L_\odot(\nu)}{L_\odot(\gamma)} = 1.4^{+0.2}_{-0.3} \left(^{+0.7}_{-0.6}\right) \tag{11}$$

At 1σ the luminosity of the Sun as inferred from neutrinos is thus determined to about 20%. Note that at 3σ the neutrino-inferred solar luminosity can be as large as (as small as) 2.1 (0.8) the precisely measured photon-luminosity.

A ^7Be solar neutrino experiment accurate to 5% could improve this determination to about 13%. The global combination of a ^7Be experiment, plus a p-p

experiment, plus the existing solar data and three years of KamLAND would make possible a really precise determination of the solar energy produced by nuclear reactions, see [42].

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References

1. J.N. Bahcall Phys. Rev. Lett. 12 (1964) 300.
2. R. Davis, Phys. Rev. Lett. 12 (1964) 303
3. SNO coll., Pys. Rev. 87 (2001) 071301.
4. K. Eguchi et al., Phys. Rev. Lett. 90 (2003) 021802.
5. SNO coll., nucl-ex/0309004.
6. M. Maltoni et al., hep-ph/0309130.
7. P.C. de Holanda and A.Yu. Smirnov, hep-ph/0309299.
8. G. Fogli et al., hep-ph/0309100.
9. G. Fogli et al., Phys. Rev. D 66 (2002) 053010.
10. G. Fogli et al., Phys. Rev. D 67 (2002) 073002.
11. J. N. Bahcall, M. H. Pinsonneault and S. Basu, Ap. J. 555 (2001) 990.
12. S. Degl'Innocenti, F. Ciacio and B. Ricci, Astr. Astroph. Suppl. Ser. 123 (1997)449.
13. H. Schlattl, A. Weiss and H.G. Ludwig, Astron. Astroph. 322 (1997) 646.
14. V. Castellani et al., Phys. Rep. 281 (1997) 310.
15. G. Fiorentin and B. Ricci, Phys. Lett. B 526 (2002) 186.
16. J.N. Bahcall, "Neutrino Astrophysics", Cambridge University Press, Cambridge 1989.
17. LUNA coll., Phys. Rev. C 57 (1998) 2700.
18. E. G. Adelberger et al., Rev. Mod. Phys. 70 (1998) 1265.
19. NACRE coll. Nucl. Phys. A 656 (1998) 70.
20. J.N. Bahcall and M.H. Pinsonneault, Rev. Mod. Phys. 67 (1995) 781.
21. J.N. Bahcall and M.H. Pinsonneault, Rev. Mod. Phys. 64 (1992) 885.
22. A.R. Junghens et al. nucl-ex/0308003.
23. A.R. Junghens et al., Phys. Rev. Lett. 88 (2002) 041101.
24. P.Descouvemant and D. Baye, Nucl. Phys. A 567 (1994) 341.
25. M. Hass et al., Phys. Lett. B 462 (1999) 237.
26. F. Hammache et al., Phys. Rev. Lett. 86 (2001) 219.
27. F. Strieder et al., Nucl. Phys. A 696 (2001) 219.
28. L.T. Baby et al. Phys. Rev. Lett 90 (2003) 022501.
29. N. Grevesse and A.J. Sauval, Space Sc. Rev. 85 (1998) 161.
30. G. Fiorentini et al., Astron. Astroph. 342 (1999) 492.
31. J.N. Bahcall et al. astro-ph/0209080.
32. V. Castellani et al. Phys. Rev. D 50 (1994) 4749.
33. J.N. Bahcall and R.K. Ulmer, Phys. Rev. D 53 (1996) 4202.
34. W. J. Dziembowski et al., Astr. Phys. 7 (1997) 77
35. B. Ricci et al. Phys. Lett. B. 407 (1007) 155.

36. G. Fiorentini et al., Astron. Astrophy. 342 (1999) 492.
37. A. Zanzi, MS Thesis, University of Ferrara, 2003
38. U. Schroeder et al. Nucl. Phys. A 467 (1987) 240.
39. C. Angulo and P. Descouvemont, Nucl. Phys. A 690 (2001) 755.
40. C. Broggini, astro-ph/0308537.
41. J.N. Bahcall, Garcia and C. Pena-Garay, Phys. Rev. Lett. 90 (2003) 131301.
42. J.N. Bahcall and C. Pena-Garay, astro-ph/0305159.